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Engineering and Design
CONTROL METHODS FOR SALINITY INTRUSION IN WELL STRATIFIED ESTUARIES AND WATERWAYS

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1. Purpose

This engineer technical letter (ETL) presents a technical description of salinity intrusion control methods that induce channel geometry changes and limit the movement of salt water beyond the control location. Enclosure 1 is a memorandum on these control methods.

2. Applicability

This ETL applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibilities for the design of civil works projects.

3. Discussion

This ETL briefly presents experimentally developed methods for limiting salinity intrusion beyond the control location where stratified flows occur. The ETL provides design guidance for the minimum height design configurations of the salinity intrusion control structures.

FOR THE DIRECTOR OF CIVIL WORKS:

1 Enclosure

PAUL D. BARBER, P.E.
Chief, Engineering Division
Directorate of Civil Works

CONTROL METHODS FOR SALINITY INTRUSION IN WELL STRATIFIED ESTUARIES AND WATERWAYS

1. Criteria outlined

This engineer technical letter (ETL) outlines criteria that have been experimentally derived for use in determination of the minimum height of a control device used in preventing saltwater intrusion beyond the control location. The guidance is based on laboratory experiments.

2. Lab experiments determine design criteria

The laboratory experiments were concerned with the development of design criteria for engineering control structures to limit intrusion of salt water into stratified estuaries and coastal waterways. Stratified estuarine flow conditions arise when mixing forces (tides and wind effects) are relatively weak with respect to stratifying forces (a large flow of low-salinity water into a high-salinity water body).

3. Idealized condition

In an idealized steady-state condition, the ocean salt water intrudes, in the form of a salt wedge, upstream against the direction of the overlying freshwater flow. The salt wedge creates a sharp interface separating the overlying freshwater and the underlying saltwater layers.

4. Control measures

In periods of lower freshwater flow, the salt water can intrude against the freshwater flow for very long distances, causing adverse economic and ecological consequences. A control structure placed in the path of the advancing salt wedge to disrupt the balance of internal forces present in the flow can limit the upstream movement of salt water beyond the control point.

5. Boundary Layer Thickness

The freshwater flow within a waterway will have density of p_f and a discharge of Q_f. Assuming that the channel is of a uniform width B and depth H, the discharge per unit width is $q_f = Q_f / (BH)$. For practical situations, it is assumed that equilibrium exists and the steady profile resembles that shown in Figure 1. The fluid layer near the bottom of the channel where the velocity profile is strongly affected by boundary shear is called the boundary layer. The thickness of the boundary layer can be characterized by two parameters: the displacement thickness

$$\delta_d = \int_o^H \frac{1}{H} \left(1 - \frac{u}{U}\right) dz \tag{1}$$

and the momentum thickness

$$\delta_m = \int_o^H \frac{1}{H} \frac{u}{U} \left(1 - \frac{u}{U}\right) dz \tag{2}$$

where $U = q_f / H$ is the mean velocity

6. Saline Wedge

If the waterway flows to a saltwater bay or ocean with a density p_s , the intrusion of salt in the waterway occurs during the upstream movement of a definable saline layer underlying the freshwater flow. This is called a saline wedge. With constant freshwater flow, water depth, and saltwater concentrations, an arrested saline wedge forms. These

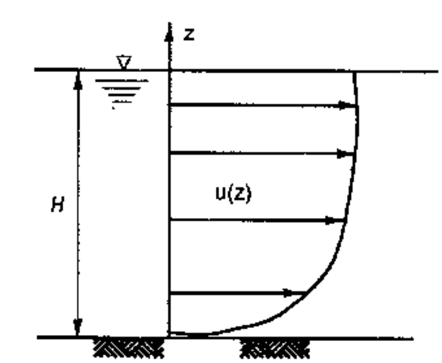

Figure 1. Velocity distribution profile of approach flow

occurrences are commonly observed in the passes of the Mississippi River and occasionally in other locations such as the Lake Washington Ship Canal in Washington and canals in Florida.

7. Densimetric Froude Number

Laboratory experiments have shown that the potential for a saltwater wedge to form increases for a densimetric Froude number F_o less than the critical value $F_{oc} = 1$. The densimetric Froude number is given by

$$F_o = \frac{q_f}{\sqrt{g'H^3}} = \frac{U}{\sqrt{g'H}} \tag{3}$$

where

g = acceleration of gravity

g' = $[(p_s - p_f)/p_f]\, g$, the buoyant acceleration

The theoretical critical value is unity; therefore, if $F_o > 1$, no saline wedge will form. In practice, however, values of F_o as low as 0.6 to 0.7 prevent the formation of a saline wedge. Therefore, for the condition $F_o < 0.6$, a salt wedge will form.

8. Internal Properties of a Saline Wedge

The internal properties of a saline wedge are shown in Figure 2. There are two distinguishable zones within the wedge: the zone or height of the density interface h_2 and the height of the zero velocity line z_2. Velocity and density distributions in the zone between these two lines are very similar. The dynamic significance of these zones is that the upper freshwater flow is turbulent, and the motion of the water exerts a high shear stress on the low turbulence underlying the saltwater layer. This shear effect tends to destabilize the upper portion of the wedge; however, it is counteracted by the strong density gradient of the saltwater layer. The density interface is not a distinct line as depicted in the figure but is mildly active with intermittent transfer and mixing of the salt water into the overlying freshwater area due to the shear effect of the freshwater flow. The lines are not of a constant height but decrease in height with distance along the length of the wedge from the ocean landward.

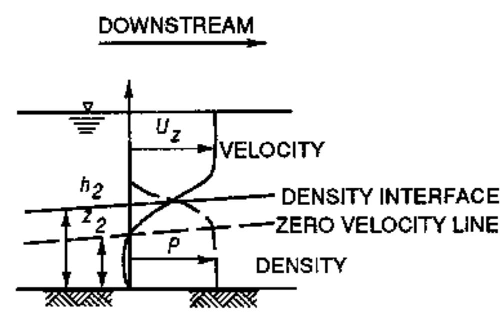

Figure 2. Internal properties of a saline wedge

9. Shape of a Saline Wedge

The shape, particularly the height (h_2 and z_2), of the saline wedge at a point in the waterway can be determined approximately by the equations of Keulegan (1966) and Schijf and Schoenfeld (1953), or more accurately, by laboratory tests and numerical modeling.

10. Saline Wedge Control

The intrusion of the salt wedge can be limited by control structures. There are three basic types of control techniques that can conceivably be used: Venturi control, static control, and dynamic control.

a. Venturi control. The basic approach with this option is just as the name implies in that a short section of the channel is constricted to form a throatlike passage. Therefore, by reducing the local width or depth, the velocities are increased and the external pressure gradient on the flowing water is reduced. The net result of this type of control is that the Froude number at the constriction increases so that it exceeds the critical value for limiting salt wedge advancement or preventing its formation. The drawback to this method is that the constrictions must be substantial to produce the desired result. Major reductions in depth or increases in flow velocity could significantly impede navigation so Venturi controls are often impractical.

b. Static control. At times it may be necessary to provide a rapidly constructed and temporary

structure to block an advancing saltwater wedge for protection of industrial and municipal fresh water supply areas. This type of control structure provides static control of the advancing wedge. It is basically a bottom barrier having an arbitrary shape but higher than the height of the local wedge (the height of the density interface in Figure 2). For this type of structure any shape can work, including a wide, broad-crested, underwater barrier similar to that shown in Figure 3.

(1) This type of structure was used in the Mississippi River in 1988 during a low river discharge period to block saltwater intrusion from the Gulf and protect freshwater intakes for the city of New Orleans. The underwater dam or sill was constructed of dredged material from an area upstream of the barrier location. The sill was constructed quickly and inexpensively provided adequate control of the saltwater intrusion (Soileau, Garrett, and Thibodeaux 1989).

(2) The basic requirement of this type of control method is that the barrier must be constructed of a height that is equal to or greater than the interface height h_2 as shown in Figure 3. An alternative to this would be to make the structure equal to the height of the zero velocity line z_2 since the flow of the advancing saltwater wedge occurs up to this height. A structure of this height can provide adequate blockage of the saltwater supply and eliminate the intrusion of the wedge. Therefore, the required static control barrier height t_d would be equal to z_2, the zero velocity point in a somewhat less conservative design.

(3) Extensive laboratory research (Jirka and Sutherland in preparation) provides accurate design criteria for the heights of the static control barriers. The experiments determined that the tentative design height for which control is obtained can be expressed as:

$$t_d \geq 1.2z_2 \tag{4}$$

and

$$t_d \geq 0.7h_2 \tag{5}$$

These equations clearly point out that simply blocking the movement of the wedge is not a sufficient form of control. The buoyancy forces of the saline wedge are sufficient to cause overtopping of the device with height equal to z_2. Therefore, the optimum height of the device is greater than z_2 but less than h_2, where z_2 and h_2 have been calculated by an appropriate method.

c. Dynamic control. Dynamic control offers a more efficient method to limit salinity intrusion. The typical hydrodynamics of the saline wedge and freshwater flow are shown in Figure 4. The approaching freshwater flow profile has a new-bed boundary layer of flow speed smaller than the main flow speed. This area of deficient velocity allows a saline wedge to more easily intrude along the bed of a channel. The concept of dynamic control, according to Jirka and Arita (1987), is to introduce into the path of the saline wedge an obstruction that both blocks the wedge and provides a sudden constriction of the approach flow, altering the near-bottom boundary layer and eliminating the zone of low flow speed. The typical ambient velocity distribution profile of the approach flow, shown in Figures 1 and 4, depicts the zone of low velocity at the near-bottom boundary layer. The end result of the dynamic control process is to produce a wedge shape similar to that depicted in Figure 5. Experimental results from the study by Jirka and Sutherland (in preparation) have shown that the average ratio of dynamic-to-static control device height is 0.8. Therefore, the height of the dynamic control device needs only to be 80 percent of the height of a static device to achieve the same performance in controlling salinity intrusion.

(1) Preliminary design criteria. A variety of devices can be used to produce the desired result. These devices range from structures resembling a sudden-step barrier or sharp-edged barrier to an elaborate method of suction at the crest of the barrier. The basic criterion for dynamic control is that the height of the device or obstruction t_d, placed in the channel to arrest the saline wedge, be on the order of the dimension of the boundary layer thickness. For a typical velocity profile, similar to that shown in Figure 1, both the boundary momentum thickness and the displacement thickness are estimated to be approximately equal to one-tenth of the water depth (H).

(2) Density current shape. In addition to the height of the dynamic control barrier, local forces must balance to maintain the shape of the density

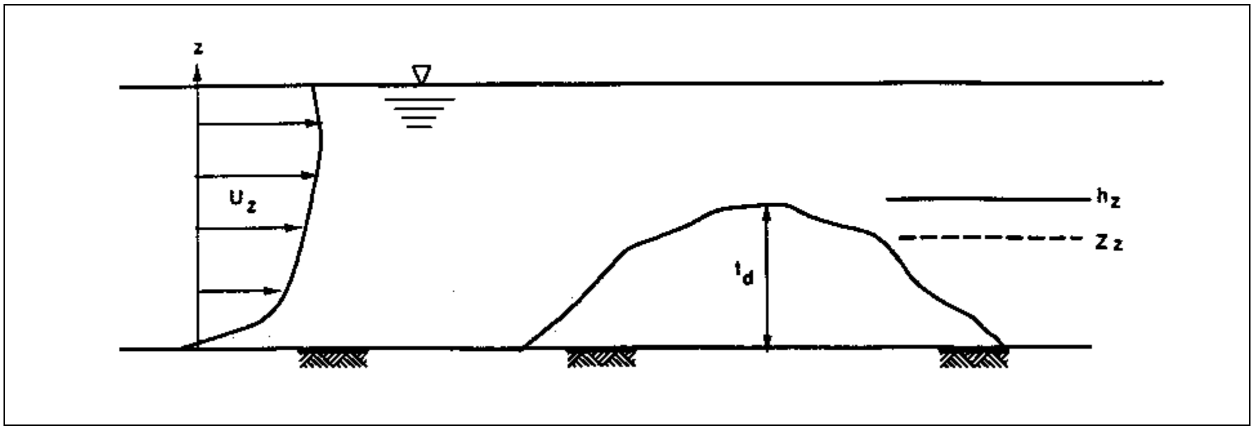

Figure 3. Static control device with arbitrary shape

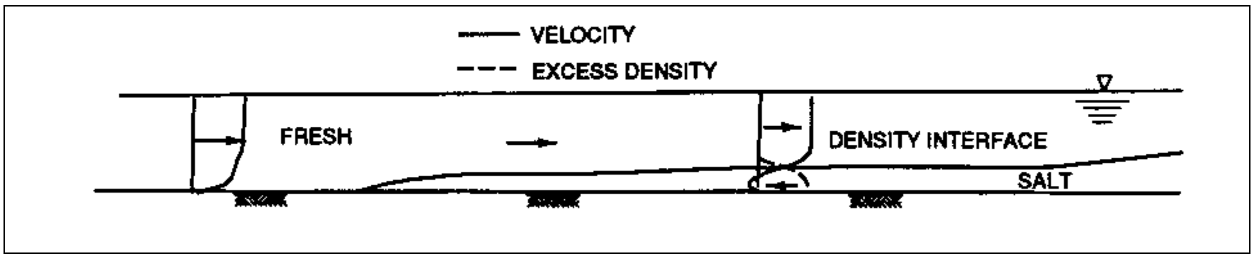

Figure 4. Saline wedge and hydrodynamic components

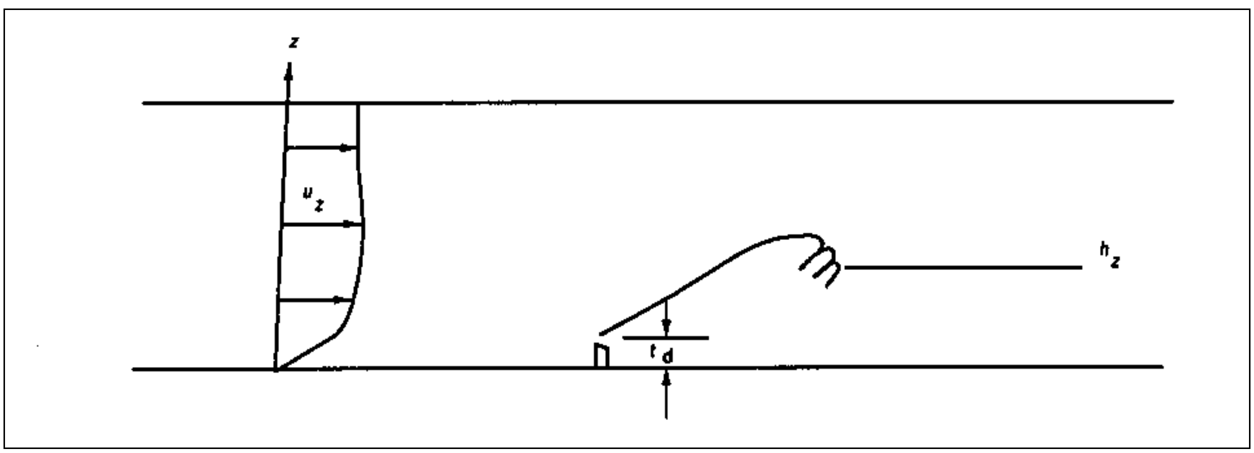

Figure 5. Dynamic control device and resulting saline wedge shape

current. According to Benjamin (1968), the density current shape is a function of the densimetric Froude number and the intrusion thickness which can be expressed as:

$$F_0^2 > \frac{n(1 - n)\ (2 - n)}{(1 + n)} \tag{6}$$

where $n = h_2/H$, the normalized height of the density interface. If the densimetric Froude number is equal to or greater than the value shown in Equation 6, the dynamic control will be effective.

(3) Height control device. If a dynamic control device of height t_d is placed on the channel bottom, it acts to block the saline wedge and creates a sudden constriction, increasing velocities at the barrier and compressing the boundary layer. The control device becomes an important factor in density current shape and must be considered in the relationship described by Equation 6. Using the control device height, Equation 6 can be reformulated as:

$$F_0^2 = \frac{(1 - n)(1 - t)(n - t)(2 - t - n)}{(1 - 2t - n)} \qquad (7)$$

where $t = t_d/H$ is the normalized barrier height. Utilizing the parameters in Equation 7 for a given combination of channel densimetric Froude number and intrusion thickness, the corresponding height of a dynamic structure for halting intrusion can be predicted using the chart shown in Figure 6. Equation 7 provides a conservative estimate of the densimetric Froude number, since assumptions are made concerning a uniform velocity profile over the control device and any mixing upstream of the device is neglected. It should also be pointed out here that for small densimetric Froude numbers, typically less than 0.1 in a river environment, the efficiency of the control device needs further investigation.

11. Saline Wedge Control Design Considerations

There are three zones of design considerations shown in Figure 6. Zone A is identified by Equation 7 and describes the combined effects of dynamic and static controls; Zone B describes the effects of purely dynamic controls; and Zone C describes the effect of purely static controls. For any combination of density interface height and Froude number which characterizes a particular channel, the height of a control device can be determined. For example, if the normalized density interface height n is less than 0.1, any channel Froude number will fall into Zone C where any static control device of height $t = n$ will provide adequate control. For values of n that are greater than 0.1 and Froude numbers that are less than or equal to 0.45, the normalized design height will be in Zone A or Zone B, combined dynamic and static devices and purely dynamic devices, respectively. Purely dynamic control devices, Zone B, of design height 0.1 will provide adequate salinity control for Froude numbers greater than 0.45 and values of n greater than 0.1.

12. Summary

Both the static and dynamic control devices can be used as methods of halting salinity intrusion. The advantage of the static control method is that the structure does not require a specifically designed shape. The disadvantage is that it relies on the height of the density interface which, if sufficiently high, could begin to impede navigation or limit flood passage depending on its location in the channel. The advantages of the dynamic controls over the static controls is that a much lower height of the structure will provide superior performance. The dynamic barrier height requirement will be approximately 80 percent of a similar static barrier to provide the same performance.

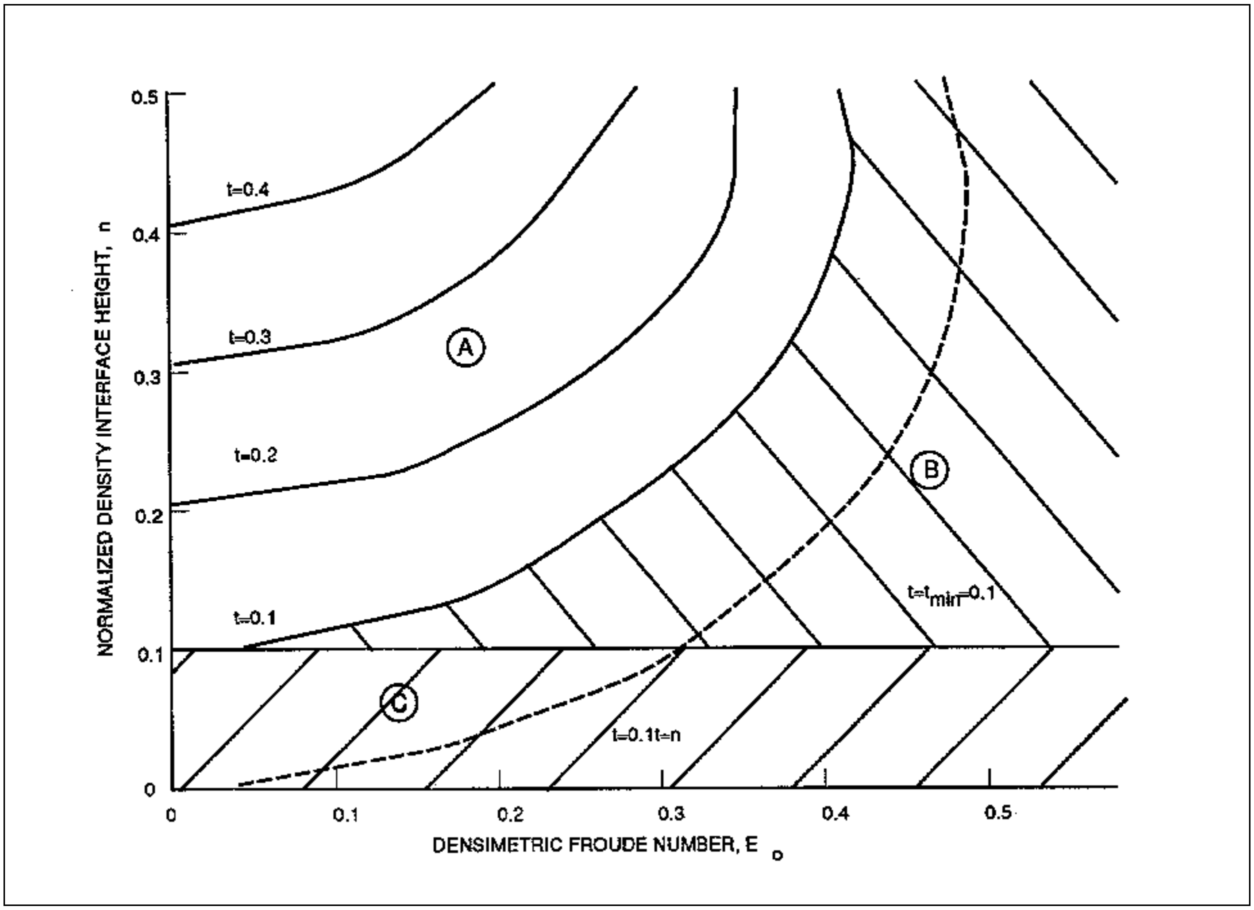

Figure 6. Design diagram for salinity intrusion control devices

EXAMPLE: Consider a river with a discharge of 58,450 cfs and an observed intruding saline wedge with an interface height of 10.5 ft. Taking the river width as 1,000 ft, the depth as 35 ft, and the density ration, $((p_s - p_f)/p_f)$, as 0.02, it is estimated that q_f = 1.67 cfs/ft, hence the Froude Number, F_0 = 0.01 and the normalized density interface n = 0.30. Using these two values to locate the point on the diagram, the value of t = 0.3 in zone A. The design height of the control device, t_d, is estimated to be 10.5 ft.

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